Effect of Fracture Healing on Laboratory-to-Field Shift Factor

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Laboratory fatigue testing of asphalt concrete can be used to predict field performance. The introduction of a shift factor is necessary to account for the effects of residual stresses and healing that occur in the field but do not occur in the laboratory. In this study the healing mechanism in asphalt concrete is investigated. A theoretical hypothesis for the shift factor and a new approach to characterizing the toughness of paving mixtures based on the J-integral concept are also introduced. The shift factor is assumed to consist of the combined effect of a strain recovery component and crack recovery component. The two components can be determined from simple laboratory tests, including stress relaxation, beam fatigue, and the overlay tests. The fracture mechanics approach, the J^*, is based on the path-independent J integral, which can be defined as the energy released per unit area of crack extension. The J^* parameter is adopted to characterize material toughness.

Loss of structural or functional pavement serviceability because of load-related fatigue cracking has long been a major topic of concern to highway engineers. Such failures often occur because of improper prediction of pavement fatigue life or premature failure from crack propagation. It is important, therefore, to understand the mode of fracture initiation and propagation for careful design of highway or airport pavements. Such understanding may lead to a procedure for estimating a shift factor between laboratory and field results that will consider the actual mechanics of fracture. Although such a factor may seem to be of little use to someone dealing with everyday pavement problems, it is of great significance for a more accurate prediction of pavement life and can be of great practical value.

The primary goal of this study is to introduce a practical approach to estimating the shift factor and to investigating and evaluating the effect of rest periods on healing fatigue-caused fractures in asphalt-treated mixtures. It is believed that the effect of healing and residual stresses that occur in the field but not in the laboratory are the major factors that will contribute to more accurate prediction of fatigue performance. In fact, prediction of field performance based on laboratory testing will normally result in miscomputation of the pavement life by a range of 300 to 2,000 percent. Identification of the healing mechanism and quantification of the effects of selected variables will, no doubt, lead to a much improved ability to predict pavement life. It will provide the basis for procedures to increase the life of asphalt structures by maximizing the healing process.

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Evidence for the existence of a healing mechanism has been provided by several laboratory studies, in addition to that produced by the AASHTO Road Test. The most detailed study has been reported by Routhly and Sterling (*1,2*), with additional evidence being provided by McElvaney and Pell (*3*), Borgin and Fourier (*4*), and Van Dijik (*5*). These studies have attempted to quantify the effect of rest periods and have expressed the result as a ratio of the number of cycles to failure with rest to the number of cycles to failure without rest. The studies mentioned above all indicate that the ratio is greater than one, that is, life measured during cyclic loading that includes rest periods is greater than life under continuous cyclic loading. These studies support the view that asphaltic materials have the capacity to recover from the effects of stress— that is, there is a healing mechanism. Previous studies have also mentioned that the healing process is affected by the rate of loading, stress level, duration of rest periods, and the method used to apply the loads.

METHODOLOGY

Although there is not much literature about healing studies for asphalt cement and asphalt concrete, there is literature about evaluating the healing of polymers. The experimental concept for the evaluation of healing has generally been to select a convenient dimensionless recovery ratio, such as the ratio of fracture stress for the virgin material to fracture stress of the healed material. In many relevant studies the healing process was described as taking place in several stages (*6,7*). Woo and O'Conner (*6*) and Jud et al. (*7*) were able to develop relations for strength, elongation to break, impact energy, and fracture parameters as a function of time, molecular weight, temperature, pressure, and processing conditions. Many of their theoretical predictions were supported by experimental data. These studies provided excellent indications that mechanical means (through the laws of fracture mechanics) can be used to determine the strength change caused by healing. In this study the energy concept is selected as the indicator for material healing. This criterion is adopted because of its engineering significance and its relative ease of measurement.

In addition, the increase in dissipated energy resulting from rest time is adopted to outline a model for the estimation of a shift factor between laboratory and field results.

The testing procedure used in this study employed the overlay tester, which was developed at Texas A&M University, College Station. The overlay tester is a fatigue testing machine designed to model displacements caused by thermal stresses in asphalt pavements resulting from cyclic changes in the

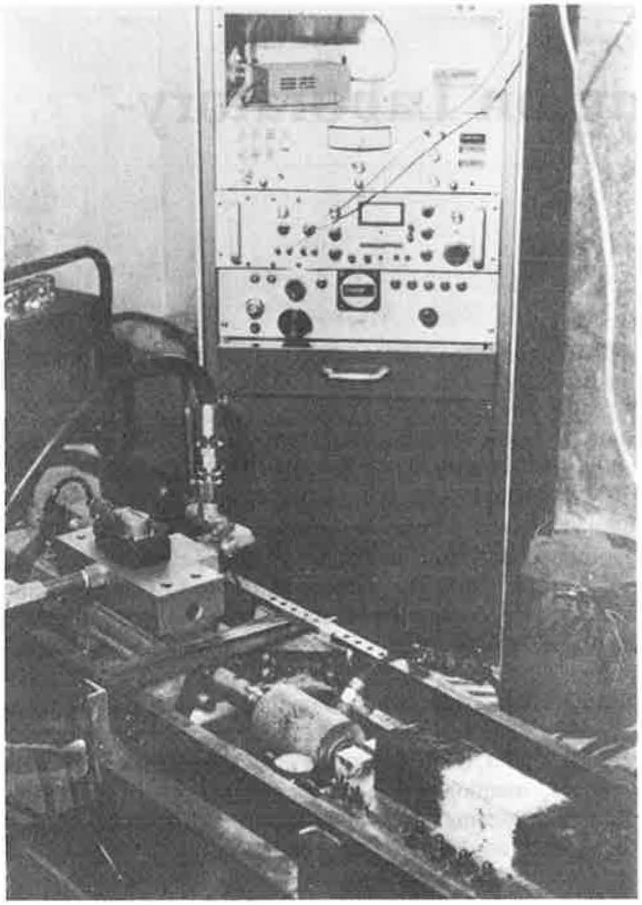

FIGURE 1 Overlay testing device.

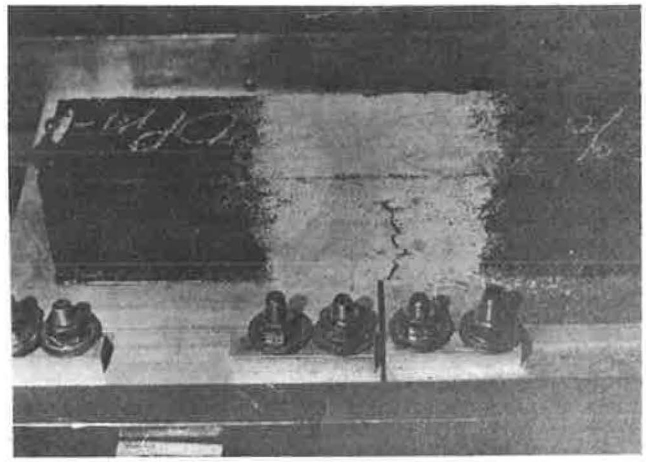

FIGURE 2 Specimen mounted on plates.

ambient temperature. A servohydraulic mechanism controls the rate of loading as well as the crack opening displacement and allows a controlled strain condition to be maintained throughout the test.

Beam samples 3 in. by 3 in. by 15 in. are prepared and then cured in an environmentally controlled room (77°F, 25 percent relative humidity) for a minimum of 3 days. Each sample is glued to a pair of aluminum base plates in an arrangement that simulates the construction of an overlay over a cracked or jointed pavement. Figure 1 shows an illustration of the testing device. Figure 2 shows an illustration of specimen mounting. The overlay tester is calibrated to ensure the desired maximum displacement of 0.04 in. or 0.02 in. A movement of 0.04 in. is approximately equivalent to the displacement experienced by a Portland cement concrete pavement with 15-ft joint or crack spacings as it undergoes a 60°F change in pavement temperature. The actual testing procedure consists of subjecting the overlay samples to an oscillating movement of opening and closing the butt joint of the two base plates. This type of movement causes a crack to form from the bottom of the sample upward through the sample. "Failure" is defined as the condition in which a continuous reflection crack is visible up both sides of the sample and across the entire width of the top of the sample, as observed when the overlay tester is in the "open" position. Under this condition, the load required to open the gap between the sample base plates is caused by the frictional forces that must be overcome to separate the two sample parts.

A loading rate of one cycle per 10 seconds was used throughout the test program. The cyclic motion was maintained except during the rest periods, during which the samples were left in the "closed" position. The load and displacement values were monitored and recorded only during selected cycles of each test. An X-Y recorder was used to plot the applied load versus displacement relationship during the selected cycles. Figure 3 shows an illustration of the X-Y plotter. Figure 4 illustrates the general shapes of typical load versus displacement graphs at various stages during the test.

ANALYTICAL APPROACH

To precisely evaluate the energy associated with fracture fatigue or, more generally, crack propagation, one must select a theoretically sound analytical approach. The science of fracture mechanics offers such an approach. Of course, asphalt cement and, in turn, asphalt concrete is not a linear-elastic material. Consequently, linear-elastic fracture mechanics is not valid. It is safe to assume that the behavior at the crack tip is nonlinear with a relatively large plastic zone preceding the crack tip. Possible methods of analysis include the crack tip opening displacement method (CTOD), *R*-curve analysis, or the *J*-integral method.

Under conditions of plane strain in which the crack tip plastic zone is small, linear elastic analysis is appropriate. For materials and conditions under which the plastic zone becomes larger, it is important that the effective crack length be used to calculate an effective stress intensity factor. However, because the plastic zone itself is a function of the stress intensity factor, an iterative process is necessary to calculate an effective stress intensity factor; as the size of the plastic zone adjustment becomes larger, relative to the crack size, the computation becomes less accurate. Under such conditions a method that permits extension of linear-elastic fracture mechanics into the elastic-plastic region must be used. The *J*-integral is best suited for the analysis of test data in this study. A major advantage of the *J*-integral method is that it does not require a stringent

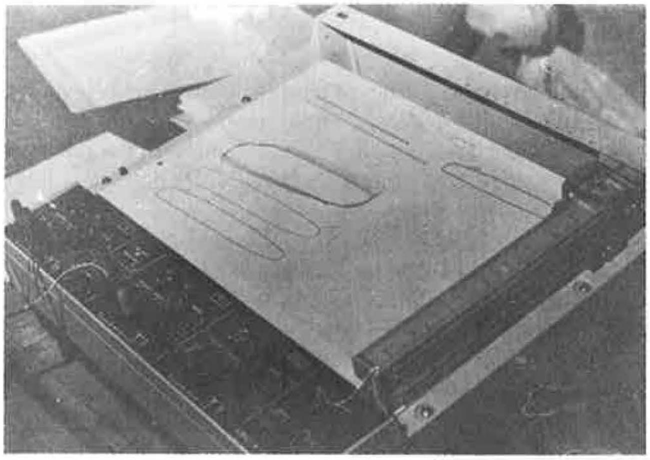

FIGURE 3 X-Y plotter.

specimen size to ensure an acceptable small plastic zone size. The method allows the determination of energy release rate (J_1) using a small specimen. Although pavement materials can be assumed to behave elastically in fracture because of their large size, size limitations of laboratory specimens prevent similar behavior. The large size of pavement constitutes a constraint to the development of a large plastic zone; thus, elastic behavior can be assumed. Conversely, the development of a large plastic zone in laboratory specimens is expected. The usefulness of the *J*-integral analysis is that one can infer information about the behavior of the elastic pavement based on laboratory specimens that may have experienced elastic deformation. The rationale is that the amount of energy released by a specific material per unit area of crack extension will be the same regardless of the size of the specimen. The *J*-integral procedure provides a way to calculate this energy release rate for an elastic material from small specimens that may have some plastic deformation.

The path-independent *J*-integral proposed by Rice (*8*) is a method of characterizing the stress-strain field at the tip of a crack by an integration path taken sufficiently far from the crack tip to be substituted for a path close to the crack tip region. Thus, even though considerable yielding occurs in the vicinity of the crack tip, if the region away from the crack tip can be analyzed, behavior of the crack-tip region can be inferred.

The *J*-integral is defined as the energy released per unit area of crack extension. It may be interpreted as the potential energy difference between two identically loaded bodies having neighboring crack size, or

$$J = -(1/B)\,(dv/da) \tag{1}$$

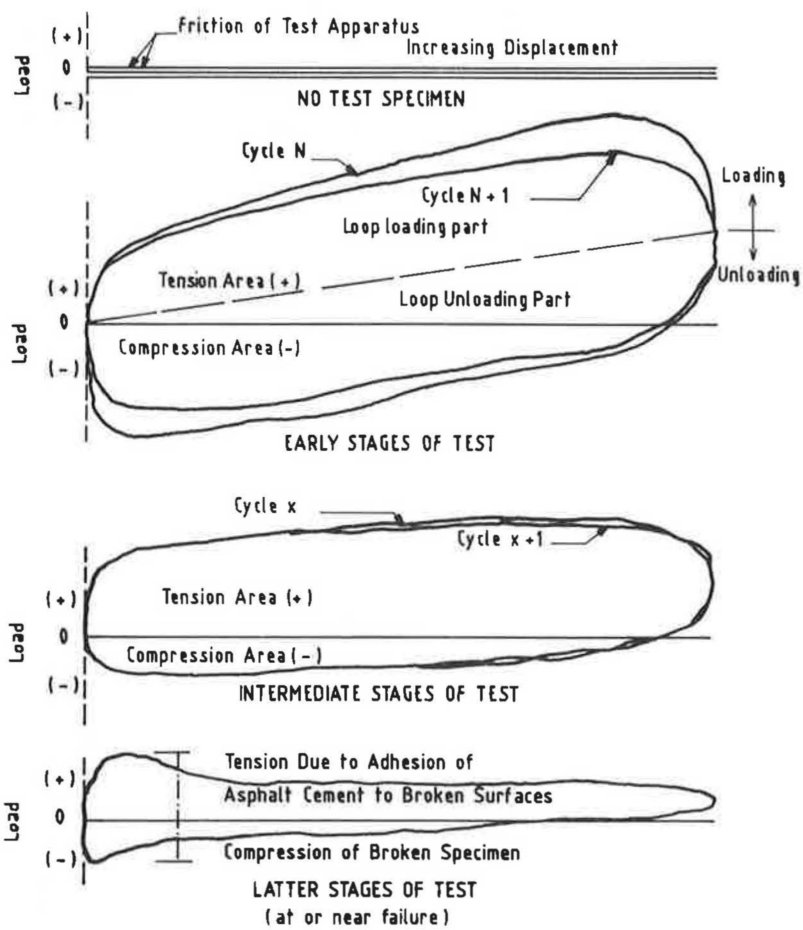

FIGURE 4 Typical recordings of load versus displacement at various stages during an overlay test.

where

V = potential energy,
B = thickness, and
a = crack depth.

This definition is shown schematically in Figure 5. A more detailed discussion of the J-integral is provided elsewhere (*8*).

Path independence of the J-integral has been shown thus far by using only the deformation theory of plasticity, which does not allow for unloading. Therefore, the J-integral fracture criteria must presently be restricted to conditions under which unloading does not occur. In the overlay test, cyclic loading and unloading of the specimen occur, which suggests that the J-integral cannot be used, because the basic definition of the J-integral is the energy released per unit area of crack extension. The difference then in the released energy between the case with unloading and the case without unloading is manifested in the area under the load-displacement curve, i.e., when unloading is considered, the V^* includes all the area enclosed by the load-displacement loop, as illustrated in Figure 4. Therefore, the parameter

$$J^* = (1/B)\ (dv^*/da) \tag{2}$$

where V^* is the energy released, including the unloading area, was adopted for analysis. The total area (V^*) reflects the energy released by the material and includes the effect of unloading. Therefore, the J^* parameter is deemed to be appropriate to characterize material toughness (the name J^* was adopted because it is analogous to the J-integral definition).

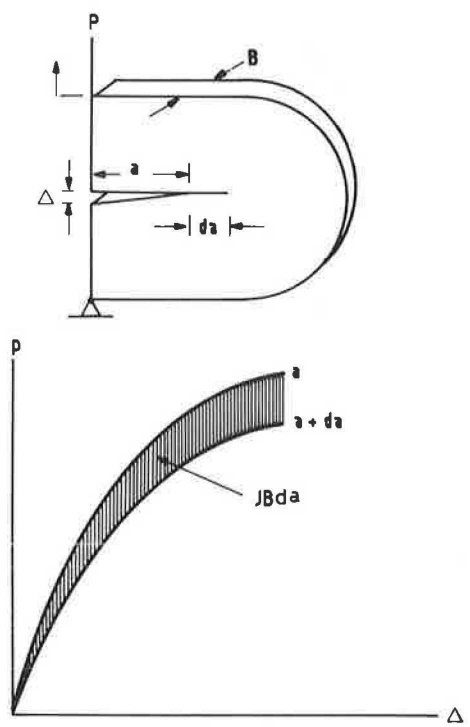

FIGURE 5 Interpretation of *J*-integral.

STUDY OF EFFECT OF REST PERIODS ON HEALING

The fatigue characteristics of pavement mixes are determined in continuous loading tests. These conditions do not resemble actual loading conditions in the field. Under traffic, the pavement is loaded discontinuously because the passage is interrupted by rest periods.

Preliminary tests of this study indicated that a single rest period had no significant effect on pavement life or fracture characteristics. To obtain a more complete insight into the effect of rest periods on the fatigue life, more tests were performed. A summary of these tests is given in Table 1.

The results of various duration of rest indicate that very long rest periods did not induce significantly greater strain recovery than did shorter rest periods. Several durations were attempted on the same specimen. Test results show that the recovery rate decreased as the test progressed. Generally, test results showed that within a rest period of between 15 and 40 minutes, a considerable proportion of the recovery can be achieved, and longer rest periods of 1 or 2 days do not substantially increase recovery. However, a 40-minute period was not much better (in terms of added energy) to a 15-minute rest period. In addition, a gap of 40 minutes between traffic vehicles in a real application occurs only on highways with very low traffic volume. Fatigue is more a problem in highways with moderate to heavy traffic. Therefore, for these practical purposes, a rest period of 15 minutes was implemented in the remainder of the tests.

Tests with a variable number of rest periods showed a very high correlation between the number of rest periods and fatigue life. The results showed an increase in fatigue life of the specimen by a factor of 2 to 5 when rest periods were introduced. These results were consistent at the two displacement magnitudes examined.

SHIFT FACTOR HYPOTHESIS

The shift factors used to transform the laboratory phenomenological fatigue model into a field "equivalent" have, in the past, been determined empirically. Perhaps the best known version was developed by Finn et al. (*9*) from AASHTO Road Test data.

Yandell and Lytton (*10,11*) conducted a detailed study of the residual stresses in a pavement. They indicated that, because of residual compressive strain, the tensile strain resulting from a wheel load application is equivalent to 80 percent of the strain that resulted from the preceding wheel load application. Furthermore, the authors presented some enlightening hypotheses on how the fatigue shift factor is affected by rest periods and residual stresses. The authors examined these hypotheses through the study of the effect of rest periods on the fatigue life of plasticized sulfur binders used in asphalt-like mixtures. These studies have substantiated their hypotheses.

During a rest period, two recovery processes may take place. In one process the material relaxes and loses some of its residual strain. In the other process the material is given time to heal from its distressed state, during which the size of the plastic zone ahead of a formed crack is reduced. During this time a portion of the crack can be closed because of the

TABLE 1 SUMMARY OF OVERLAY TESTS

Displacement magnitude (in)	With rest periods	Without rest periods					
	No. of Specimens						
0.02	4	4					
0.04	4	4					
	Rest period duration (hr.)						
	1	4	24				
	No. of specimens						
0.02	2	1	1				
0.04	2	1	1				
	Number of rest periods						
	1-10	11-20	21-30	31-40	41-50	51-60	No. rest
	Number of specimens						
0.04	2	2	2	2	2	2	2

compression resulting from bond forces between the particles of the material after the removal of the applied load. These two effects will result in increasing the expected fatigue life of a specimen.

Considering the fact that a field loading pattern is similar to laboratory loading with rest periods, an analytical approach can be postulated to estimate a shift factor between laboratory and field results. In this approach the shift factor is assumed to consist of two components as follows:

$$SF = (SF_r)\ (SF_h) \tag{3}$$

where

SF_r = the shift caused by residual stresses, and
SF_h = the shift caused by crack healing and plastic zone reduction.

The behavior of the material during the residual strain component (SF_r) is very much analogous to relaxation characteristics and strain recovery characteristics. This behavior permits the assumption of similar decay and recovery patterns. The stress relaxation relationship can be presented in the form

$$E(t)/E_0 = t^{-n} \tag{4}$$

where

$E(t)$ = the elastic modulus at time t,
E_0 = the initial elastic modulus, and
n = the slope of the relaxation curve.

The ratio of the strain at a given time to the initial strain $[P(t)/(P_0)]$ can be fitted to a relationship of the following form:

$$P(t) = 1 - (1 - P_0)t^{-n} \tag{5}$$

To reflect this characteristic pattern on the expected fatigue life, the following relationship is assumed:

$$SF_r = \left\{1/\left[1 - (1 - p_0)t^{-n}\right]\right\}^{k2} \tag{6}$$

where k_2 is the slope of the beam fatigue laboratory relationship between the number of cycles to failure (N_f) and initial strain.

The shift factor component related to crack healing is estimated on the basis of rest period analysis. These analyses revealed a relationship between added energy and the logarithm of rest duration of the form

$$du = e^{h \log t} \tag{7}$$

where

du = the added energy,
t = time, and
h = constant.

The analysis also revealed a direct relationship between the amount of added energy and the increment in specimen life of the form

$$d\ n_f = a + m\ (du) \tag{8}$$

Combining the last two equations gives

$$d\ n_f = a + m\ (e^{h \log t}) \tag{9}$$

Using the above equation with coefficients developed experimentally, dn_f, and consequently n_f, were computed for various time periods. Furthermore, a relationship between cycles to failure and number of rest periods was developed (Figure 6) from the analysis of rest periods. Using this relationship, the corresponding number of rest periods (n_r) for the computed N_f was determined. The variable $(n_f/n_0 - 1)/n_r$, where n_0 is the fatigue life without rest, was then computed for the various time periods. A relationship of the following form was then fitted to the computed variables:

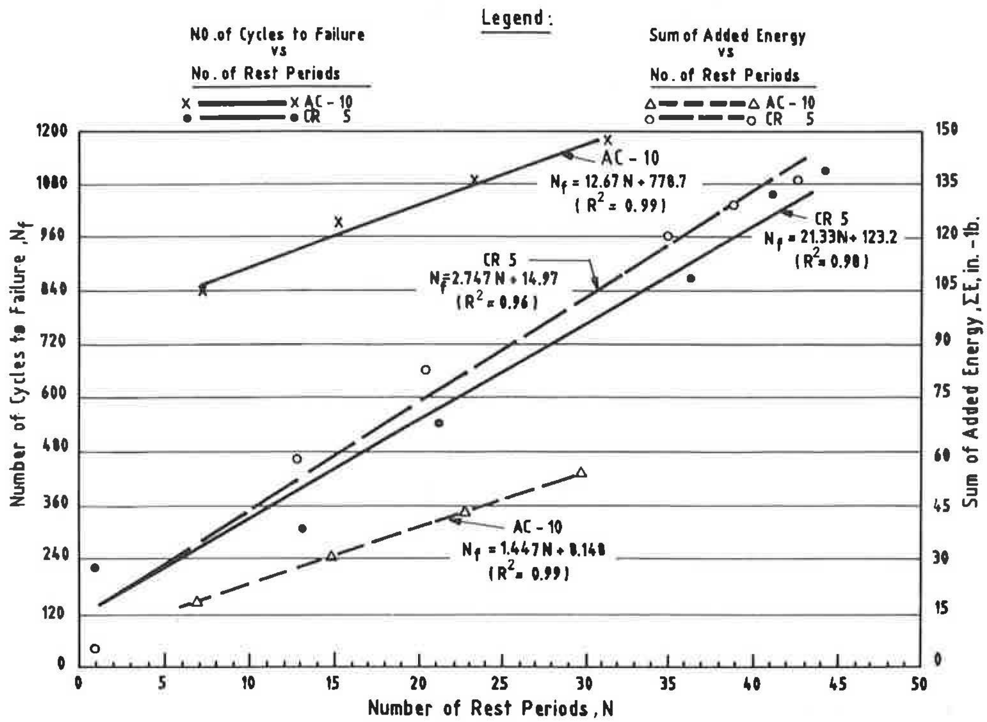

FIGURE 6 Relationships between (a) number of cycles to failure and number of rest periods and (b) sum of added energy and number of rest periods.

$$(N_f/N_0 - 1)/n_r = 5.685 \times 10^{-3}\, e^{1.956(\log t)} \tag{10}$$

which can be reduced to

$$(N_f/N_0) = 1 + 5.685 \times 10^{-3}\, e^{1.956(\log t)} \tag{11}$$

Combining the two shift factor proportions yields

$$SF = \left\{1/\left[1 - (1 - p_0)\, t^{-n}\right]\right\}^{k2} \times \left[1 + 5.685 \times 10^{-3}\, e^{1.956(\log t)} n_r\right] \tag{12}$$

Using a K_2 = 2.998 (a typical slope coefficient developed for plasticized sulfur binders in beam fatigue tests) and typical slope values of stress relaxation curves (n) for the same materials, with various numbers of rest periods (n_r), several combinations of SF_r and SF_h were computed and are presented in chart form in Figure 7. The chart can be used to select the two components of the shift factor that correspond to a certain rest time. The total shift factor will be the product of the two components. Asphalt cement (AC-10) is expected to have a higher shift factor because it showed better healing characteristics. Test results indicate a K_2 value of 3.726 for asphalt cement (AC-10). This will result in higher values for SF_r and, consequently, a higher overall shift factor.

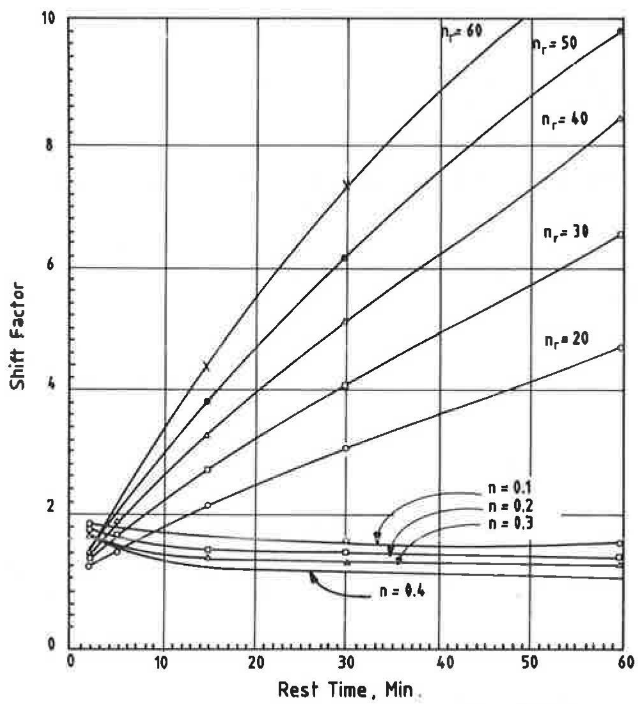

FIGURE 7 Shift factor chart.

TABLE 2 LABORATORY-TO-FIELD SHIFT FACTORS USED FOR ASPHALT CONCRETE AND SULPHLEX

	Shift Factors		
N_{lab}	T = 36°F	T = 68°F	T = 110° F
10^2	18.8	12.9	7.9
10^3	10.5	7.7	5.3
10^4	5.8	4.6	3.5
10^5	3.2	2.8	2.5
10^6	1.8	1.7	1.5
10^7	1.0	1.0	1.0
10^8	0.56	0.60	0.66

All parameters on the righthand side of the shift factor relationship can easily be determined from laboratory tests. Coefficients of the crack healing portion can be determined from overlay tests with rest periods. The n parameter can be determined from a relaxation test and the K_2-parameter can be determined from a simple beam fatigue test. This relationship presents a simple, practical, and convenient means to estimate a shift factor between laboratory and field results.

ANALYSIS OF TEMPERATURE EFFECT

To illustrate the effect of temperature on the shift factor and to demonstrate the field conditions for comparative analysis it was necessary to represent field conditions. The shift factors suggested by Pickett et al. (*12*) (Table 2) were selected for both asphalt concrete and Sulphlex for the following reasons:

1. Utilization of identical shift factors for asphalt and Sulphlex is considered an acceptable approach until field verification indicates that different factors should be used,
2. The rest period analysis points out a similar healing response for Sulphlex CR5 and AC-10 specimens, and
3. Shifting AC-10 laboratory beam fatigue data by means of the Pickett factors yields a realistic failure criterion, which is comparable to that of Finn et al. (*13*) (Figure 8).

The time-temperature shift factors (a_T) for Sulphlex and asphalt mixtures with various aggregates and gradations were then compared and are shown in Figures 9 through 11. The following are apparent from these figures:

1. Shift factors for asphalt concrete and Sulphlex for each mixture evaluated were similar. In fact, the effect of binder on a_T was not statistically significant.

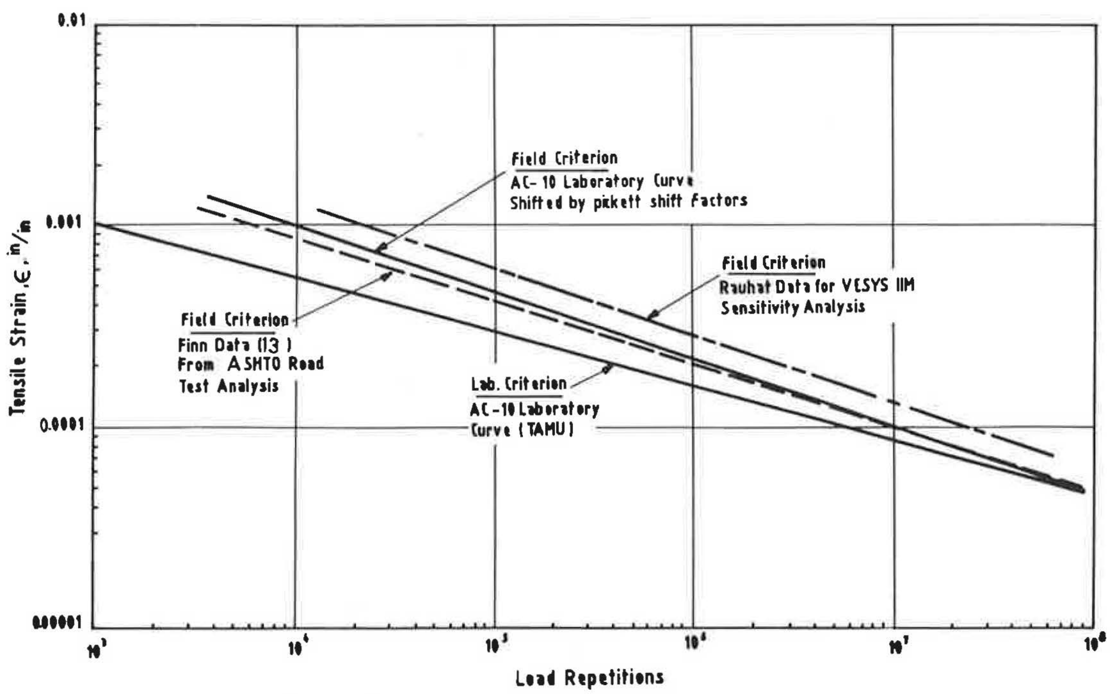

FIGURE 8 Illustration of laboratory-to-field shifts.

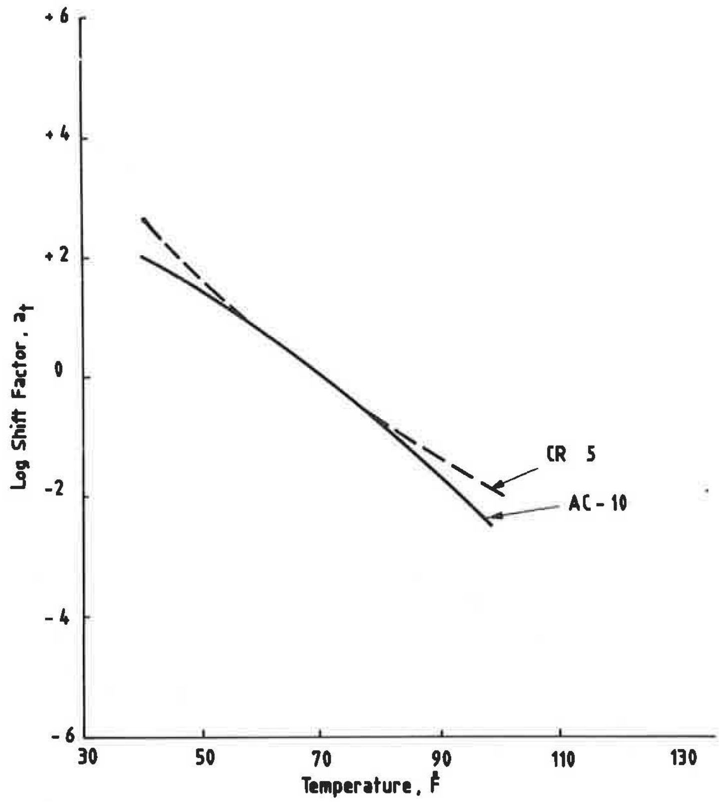

FIGURE 9 Time-temperature shift factor for mixtures with crushed limestone aggregates.

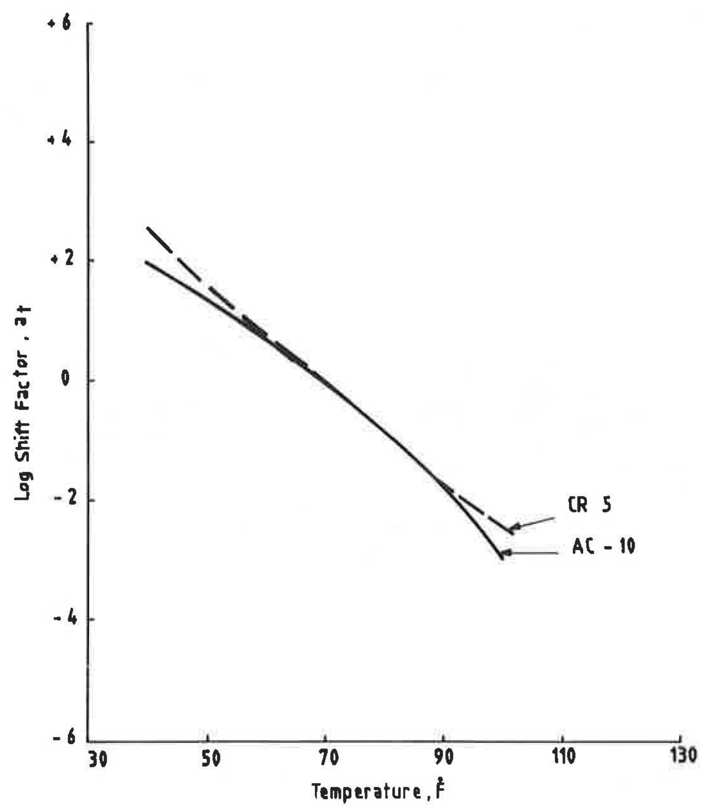

FIGURE 10 Time-temperature shift factor for mixtures with basalt aggregate.

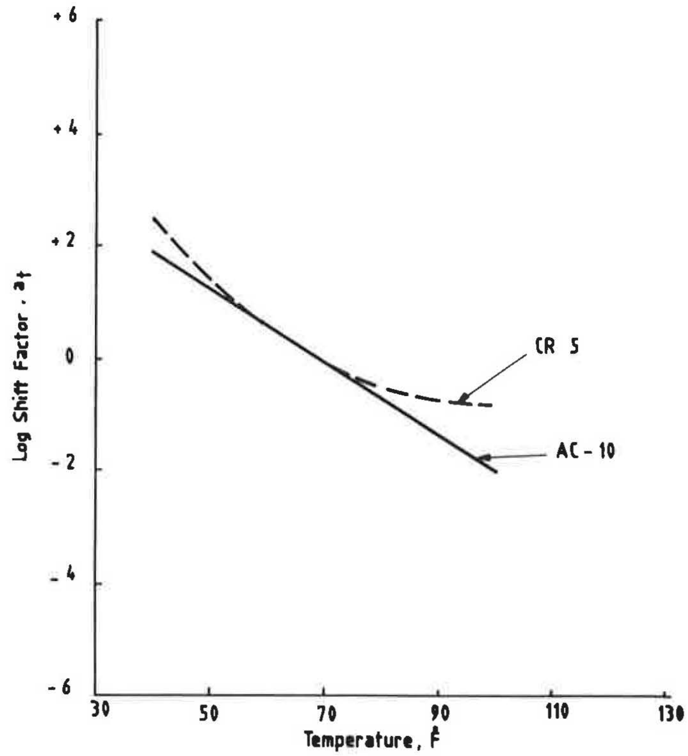

FIGURE 11 Time-temperature shift factor for mixture with river gravel aggregate.

2. Ranges of shift factors between 100°F and 40°F are typical of those found in the literature for asphalt concrete (*12*) and sulfur extended asphalt mixtures.
3. The effect on the shift factor of aggregate type was as great as that of binder type.

Although for practical engineering purposes both Sulphlex and asphalt concrete can be considered linearly viscoelastic, the application of a horizontal shift factor along the log time abscissa to produce a master curve is subjective. The value becomes even more subjective when the shift factor is described in terms of beta. The term beta is defined as the ratio of the change in $\log_{10} a_T$ over a change in temperature or a temperature interval.

$$\text{Beta} = \text{Delta}(\log_{10} a_T)/\text{Delta } T \quad (13)$$

This value assumes a linear relationship between $\log_{10} a_T$ and temperature. As can be seen from Figures 9 through 11, this relationship is not the case. The values of beta are presented in Table 3.

CONCLUSIONS

In this study a new approach to characterizing the fracture behavior of paving mixtures has been introduced. A modified form of the *J*-integral was implemented. The modified form is based on the total area under the load displacement curve that includes the unloading portion instead of just the loading area in the conventional *J*-integral approach. A major advantage to this approach is the ability to extend the analysis into the elastic-plastic region, thus eliminating the requirements for a stringent specimen size to ensure plane strain conditions.

The analysis of rest periods indicated a direct relationship between the number of rest periods and fatigue life. The analysis showed that an increase in fatigue life results from an increase in the number of rest periods. Additionally, the rate of incremental benefit from rest periods diminishes as the duration of the rest period increases (Figure 12). The rate of added energy decreases substantially for rest periods longer than 30 minutes. The recovery trend as a function of time can be described by an exponential function. Material recovery patterns as a function of crack length resemble energy release patterns.

The theoretical basis for a shift factor is presented based on Lytton's hypothesis. The shift factor is assumed to consist of the combined effect of a strain recovery component and crack recovery component. The two components can be determined from simple laboratory tests consisting of stress relaxation, beam fatigue, and overlay tests. Limited rest period testing on AC-10 specimens and CR5 specimens at room temperature reveal that although the fracture propagation life (N_f) is superior for AC-10 specimens compared with that for CR5 specimens, healing properties at 73°F are similar.

TABLE 3 SUMMARY OF BETA VALUES

Binder	Aggregate	Air Voids Content,%	BETA
AC-10	CLS	6-8	0.080
		3-5	0.070
		3-5	0.090
	RG	2-3	0.095
	Basalt	3-5	0.089
CR5	CLS	3-5	0.075
	Basalt	6-8	0.070
	RG	2-3	0.080

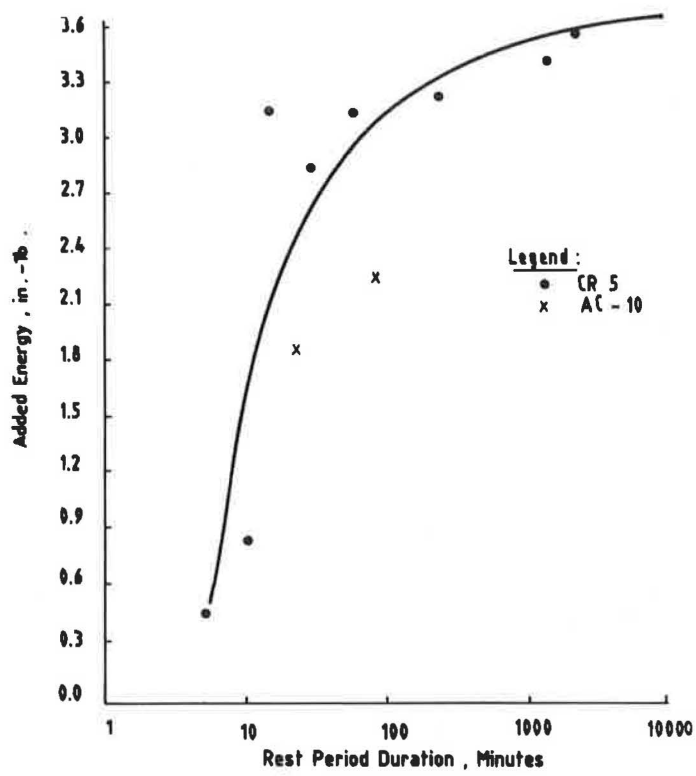

FIGURE 12 Effects of duration of rest period on energy required for crack propagation (specimens were CR5 and crushed limestone).

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Publication of this paper sponsored by Committee on Flexible Pavement Design.